System level TVAC functional testing for the Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) payload destined for the International Space Station

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ABSTRACT

The Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) payload will be launched to the International Space Station (ISS) in 2023. ILLUMA-T is an optical communications payload that will make the ISS the first space-based user to communicate with NASA's Laser Communications Relay Demonstration (LCRD). The system will support all-optical forward links up to 150 Mbps and return links up to 1 Gbps. The payload recently underwent system level Thermal VACuum (TVAC) functional testing at MIT Lincoln Laboratory. We present an overview of the payload's TVAC functional tests and results.

Keywords: free-space optical communication, laser communication, lasercom, human space exploration

1. INTRODUCTION

NASA's interest in lasercom began with the very successful Lunar Laser Communication Demonstration (LLCD) which demonstrated a 622 Mbps optical downlink and a 20 Mbps optical uplink, both error free, over a variety of different conditions in 2013 [1]. The LLCD payload was designed, built, and operated by MIT Lincoln Laboratory (MITLL) and the payload design and ops concept were used by NASA for the Laser Communication Relay Demonstration (LCRD) [1]. A subsequent effort at MITLL resulted in the development of a novel Modular, Agile, Scalable Optical Terminal (MAScOT) [3]. This MAScOT architecture is to be employed in both the OpCom payload (O2O Mission) on Artemis II and the Integrated LCRD Low-Earth-Orbit (LEO) Modem and Amplifier Terminal (ILLUMA-T) [4], a follow-on program to LCRD which provides a high bandwidth lasercom link to/from the International Space Station [5]. ILLUMA-T allows the ISS to be the first LEO user of the LCRD optical comm link, providing a forward communications link at 51 or 155 Mbps and a return communications link at 155, 311, 622, or 1244 Mbps.

ILLUMA-T was integrated and tested at the functional level, over temperature and in vacuum, at MITLL in the spring of 2022 and then delivered to NASA GSFC to continue with mechanical integration into the full ILLUMA-T payload, further testing, and delivery to NASA KSC in 2023. In order to assure ILLUMA-T meets its performance requirements, we devised a functional test plan which was performed during Thermal VACuum (TVAC) testing at MITLL. TVAC testing examines how the terminal performs under the extreme hot and cold conditions experienced on the spacecraft. This performance testing will be described and reported on in this paper.

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2. ILLUMA-T DESCRIPTION

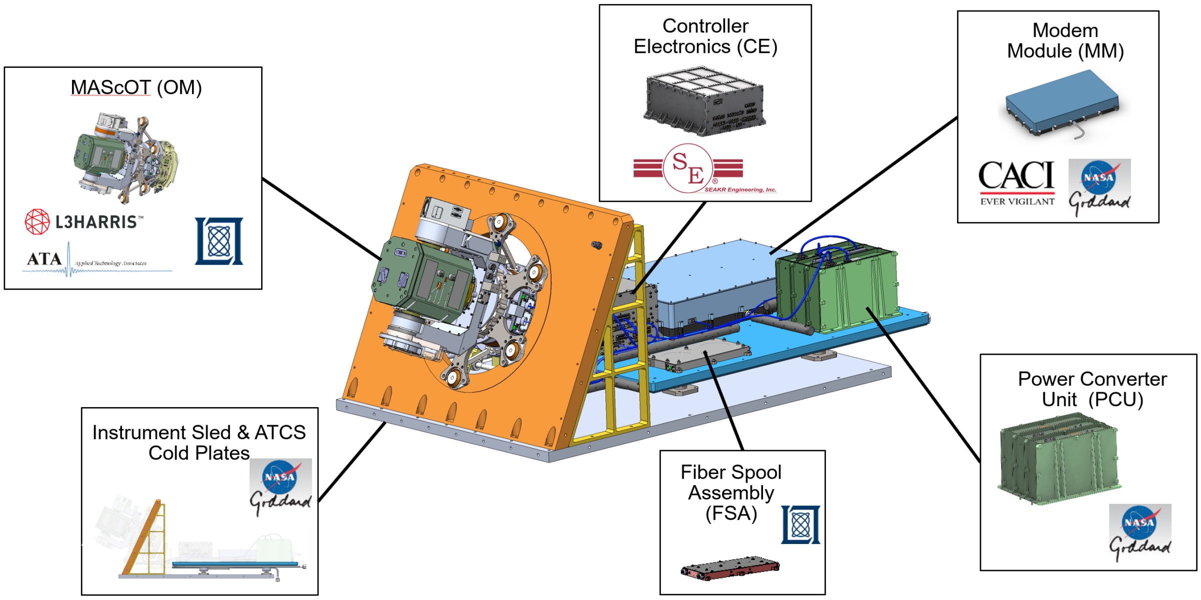

Figure 1: ILLUMA-T "sled" consists of 6 subsystems: the MAScOT Optical Module (OM), the Controller Electronics (CE), the Modem Module (MM), the Power Convertor Unit (PCU), the Fiber Spool Assembly (FSA), and the Instrument sled and Active Thermal Control System (ATCS) cold plates.

ILLUMA-T consists of several modules, or sub-systems, depicted in Figure 1. The sled design is consistent with the form factor required for installation on the Japanese Experiment Module (JEM), known as "Kibo." The optical beam is pointed using the MAScOT Optical Module (OM) which was designed and integrated by MIT Lincoln Laboratory [6] using subsystems obtained from L3Harris and ATA. The OM features a gimbaled telescope to receive/transmit comm signals, a wide FOV sensor for Point-Acq-and-Track (PAT), alignment mirrors to adjust the boresights of the transmit and receive beams, and a fast steering mirror which tracks out spacecraft jitter using a control loop. The OM is connected to the Modem Module (MM) via three optical fibers for transmit, receive, and beacon signals. The Modem Module (MM) generates the comm transmit signal for the return link from an 100Mb or 1Gb Ethernet input from the ISS and receives and decodes an incoming forward link signal providing an Ethernet output to the ISS. The MM also can generate a modulated beacon signal which is used in the cooperative PAT process with the remote terminal. The MM was specified by NASA GSFC and built by CACI and is compatible with the LCRD modem described in Ref. [7]. For ILLUMA-T, only the Differential Phase Shift Keying (DPSK) format was implemented at 1.5 µm wavelength. The Power Converter Unit (PCU) was designed and built by NASA GSFC; it takes the 120 V ISS power and converts it to 28 V required for the payload operation. The Controller Electronics (CE) was specified by MITLL and built by Seakr Engineering; the CE performs real-time pointing control for the OM as well as processes commands and telemetry. The Fiber Spool Assembly (FSA) is a tray designed to hold and protect excess optical fiber and fiber splices between the OM and the MM. The Instrument Sled and Active Thermal Control System (ATCS), designed by NASA GSFC, uses coolant supplied by the ISS to regulate the temperature of the payload. The assembled ILLUMA-T "sled" for testing at MITLL is shown in Figure 2.

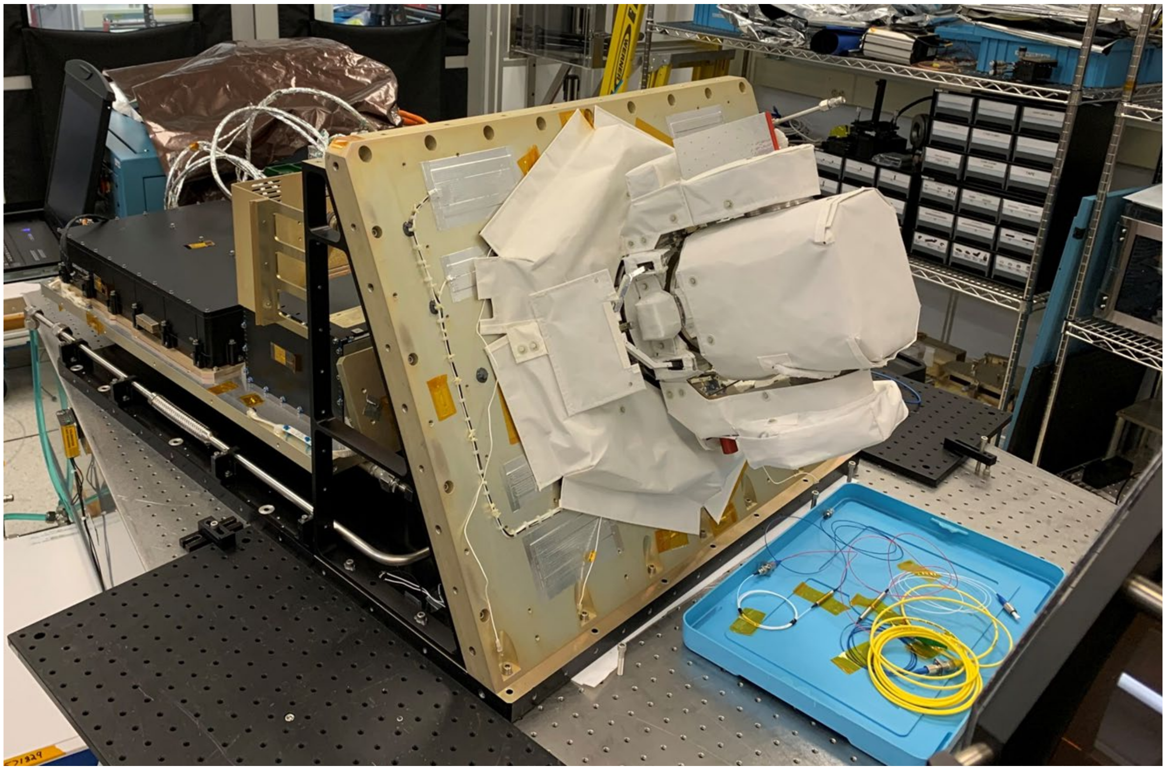

Figure 2: ILLUMA-T "sled" ready for testing at MIT Lincoln Laboratory.

3. TEST FACILITIES AND TEST PLAN

System level testing was performed at MITLL in a Class 1,000 clean room containing a DynoVac TVAC chamber. The thermal profile for the TVAC performance testing is shown in Figure 3 and is based on NASA's General Environmental Verification Standard (GEVS)[2]. Since the ATCS is used, the temperature extremes experienced when the terminal is powered on are not as extreme as one would expect. Prior to testing, the terminal underwent a full comprehensive performance test. Once the TVAC chamber is pumped down, the terminal experiences thermal survival cycling while powered off. The terminal is then powered on and undergoes the required number of hours of hot and cold plateaus. System level performance testing is done at cold, nominal, and hot plateaus. After the thermal cycles, the terminal is powered down and the TVAC is allowed to return to ambient pressure after which a comprehensive performance test is performed prior to removal from the chamber.

ILLUMA-T was tested using the MOTS (MAScOT Optical Test Set). The MOTS emulates the free space link and also contains a number of sensors for various sub-system measurements. MOTS can truncate the return link from the OM to a flat-top beam and also transmit a large flat-top beam to the OM to simulate the forward link. The MOTS contains two features relevant to system level testing: a high speed camera to measure boresight and pointing performance as well as a fast steering mirror to emulate spacecraft jitter.

Since ILLUMA-T provides the LEO user side of the comm link, an LCRD terminal emulator is required to test the end-to-end comm link. The LCRD terminal emulator was provided by NASA in the form of a stand-alone rack-mounted LCRD modem.

[2] https://standards.nasa.gov/standard/GSFC/GSFC-STD-7000

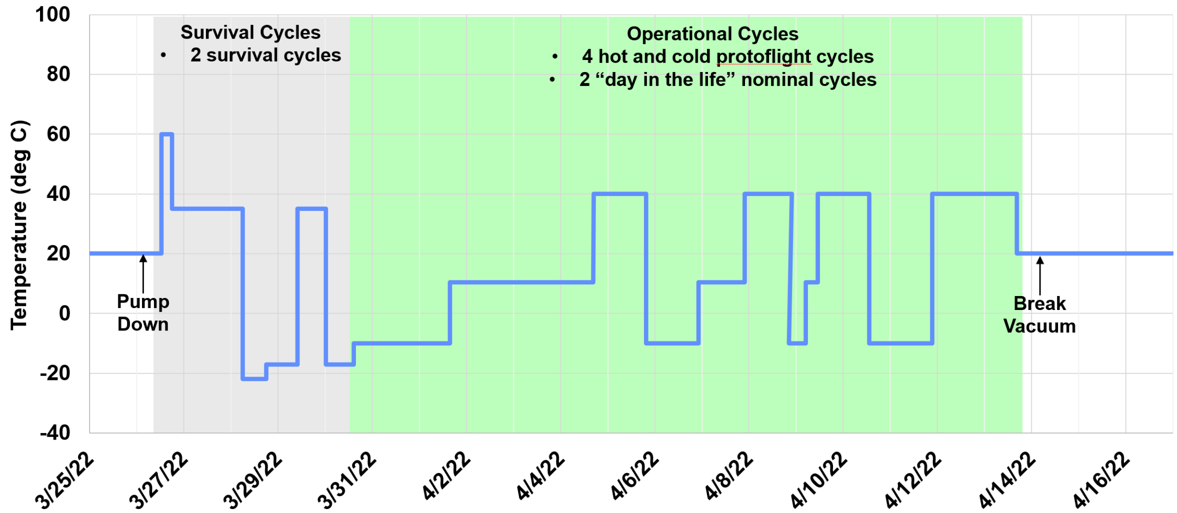

Figure 3: As-run thermal profile for ILLUMA-T TVAC testing

4. SYSTEM TESTING

The goal of ILLUMA-T system level testing was to test comm performance in TVAC for a reasonable number of cases with realistic conditions. We elected to focus our comprehensive testing on two cases: 622 Mbps return link with 51 Mbps forward link and 1.244 Gbps return link with 155 Mbps forward link. Comm performance for these two cases were tested under many conditions including: fine tracked with and without jitter, varying beacon to comm power ratios, different output total powers, tracking with the OM at different elevation/azimuth positions, and different beacon modulation frequencies. Comprehensive testing was performed at both the optical layer and at the link layer. For link layer testing, we examined 100M and 1G Ethernet performance. Abbreviated comprehensive tests were also done at 155 Mbps return / 51 Mbps forward, 311 Mbps return / 51 Mbps forward, and 622 Mbps return / 155 Mbps forward. This complete set of testing was performed pre- and post-TVAC and at one of each of hot, nominal, and cold plateaus during TVAC. In order to maximize testing, we also performed limited testing at as many additional hot, cold, and nominal plateaus. Limited performance tests were scaled-down, low-power comm tests that aimed to look for changes in performance.

5. RESULTS

An example of ILLUMA-T return link results is shown in Figure 4. The comm performance results are shown for 622 Mbps and 1244 Mbps, without jitter, for a variety of temperatures and pressure conditions as labelled. As this testing was primarily about the space terminal system level performance, the required performance is to minimize impairment to the signal under all the tested configurations in TVAC. As can be seen from this representative figure, the required performance was achieved.

An example of ILLUMA-T forward link results is shown in Figure 5. This figure shows comm performance 51Mbps including jitter for 3 different temperatures (cold, nominal, and hot) as well for different azimuth and elevation and beacon modulation frequencies, as labeled in the figure. Since it is not possible to test with varying comm power levels without affecting tracking performance, we relied on theoretical predictions to show that we meet the -70 dBm required power for error free operation at 51 Mbps.

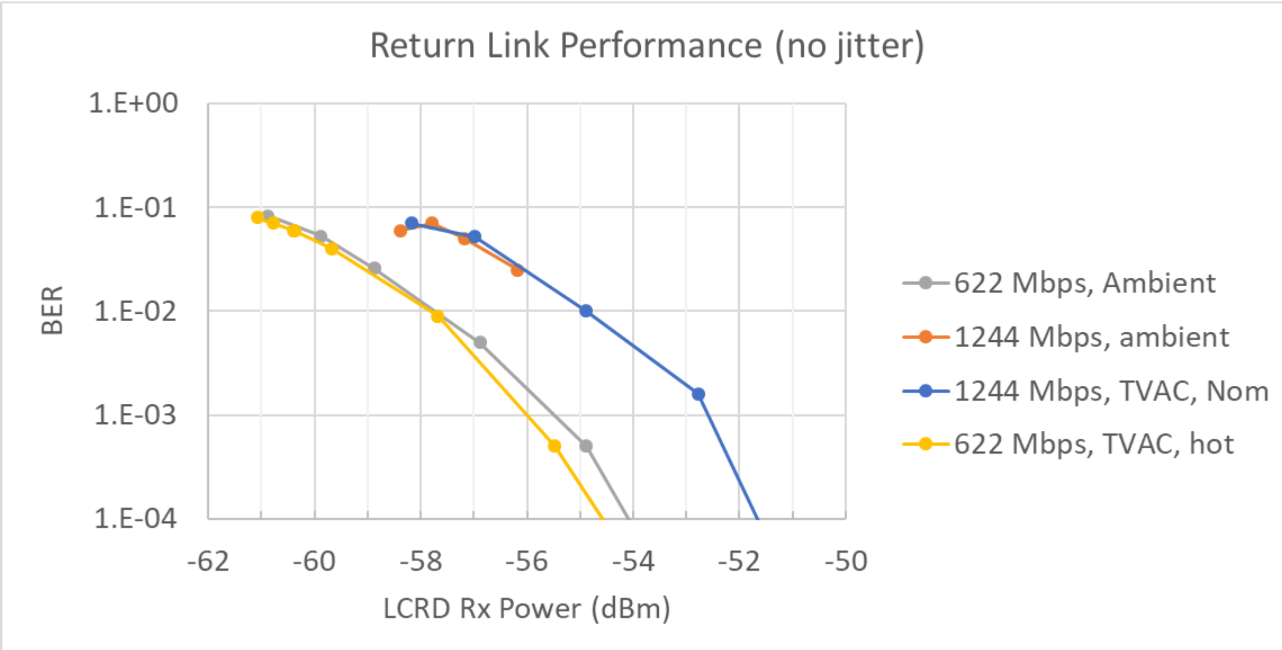

Figure 4: Return link results showing LCRD received power vs. Bit Error Rate (BER) for 622 Mbps and 1244 Mbps signals. The cases are shown for ambient, nominal, and hot temperatures and spacecraft jitter is turned off.

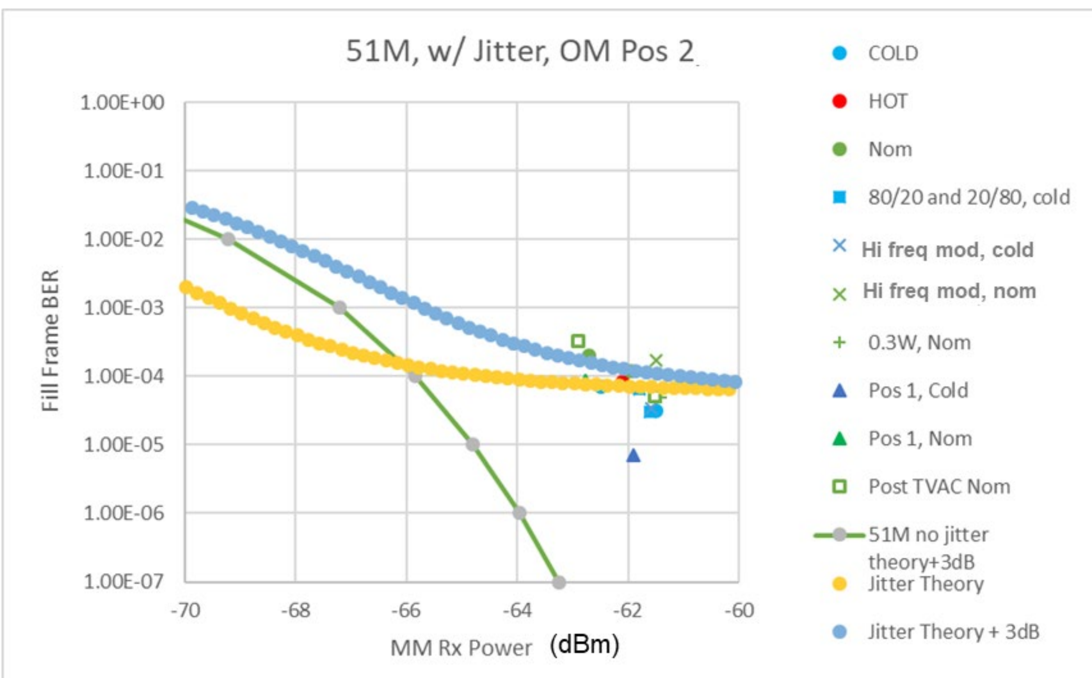

Figure 5 Forward link results showing Modem received power vs fill frame Bit Error Rate (BER) for 155 Mbps signal. The cases are shown for nominal, cold, and hot temperatures with spacecraft jitter.

6. CONCLUSIONS

System TVAC testing on ILLUMA-T has been performed at MITLL and shows that the system is meeting its performance specifications. The terminal has been shipped to NASA GSFC for further integration and testing before it is manifested on Space X Dragon to be flown to and installed on the ISS in 2023.

REFERENCES

[1] Boroson, D.M., Robinson, B., Murphy, D., Burianek, D., Khatri, F., Kovalik, J., Sodnik, Z., and Cornwell, D., "Overview and results of the Lunar Laser Communication Demonstration," in *[Free-Space Laser Communication and Atmospheric Propagation XXVI], Proc. SPIE* **8971** (2014).

[2] Israel, D.J., Edwards, B.L., and Staren, J.W., "Laser Communications Relay Demonstration (LCRD) update and the path towards optical relay operations." IEEE Aerospace Conference (2017).

[3] Shih, T., Gulder, O., Khatri, F., DeVoe, C, Hubbard, W., Constantine, S., Torres, J., and Robinson, R., "A modular, agile, scalable optical terminal architecture for space communications, IEEE ICSOS Conference (2017).

[4] Seas, A., Robinson, B., Shih, T., Khatri, F., and Brumfield, M., "Optical communications systems for NASA's human space flight missions," International Conference on Space Optics—ICSO Vol. 11180 (2018).

[5] Robinson, B. S., T. Shih, F. I. Khatri, D. M. Boroson, J. W. Burnside, O. Guldner, S. Constantine et al. "Laser communications for human space exploration in cislunar space: ILLUMA-T and O2O" in *[Free-Space Laser Communication and Atmospheric Propagation XXX], Proc. SPIE* **10524** (2018).

[6] Gillmer, S.R., Smeaton C.V., Burnside, J.W., Torres, J., Hubbard, W., Bennett, C., DeVoe, C., Wellman J.A., Rey, J.J., Zervas, M.J., Khatri, F.I., Shih, T., Guldner, O., Padula, M., Robinson, B.S., "Demonstration of a modular, scalable, laser communication terminal for human spaceflight missions," in *[Optical Engineering + Applications] Proc. SPIE* **11816** (2021).

[7] Krainak, M.A., Luzhanskiy, E., Li, S.X., Merritt, S.A., Yu, A.W., Butler, R., Badgley, J., Thomas, L., Stello, H., Cheng, A., Nguyen, Q., MacPherson, S., "A dual format communication modem development for the Laser Communications Relay Demonstration (LCRD) program," in *[Free-Space Laser Communication and Atmospheric Propagation XXV] Proc. SPIE* **8610** (2013).